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1 411 136

(54) APPARATUS FOR SEPARATING FINELY DIVIDED SOLID PARTICLES FROM AN ENTRAINING GAS

(71) We, SHELL INTERNATIONALE RESEARCH MAATSCHAPPIJ N.V., a company organised under the laws of The Netherlands, of 30 Carel van Bylandtlaan, The Hague, The Netherlands, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed to be particularly described in and by the following statement:—

The removal of finely-divided solid particles from entraining gases is necessary in almost any system in which the gas is to be passed through a fluid dynamic device containing gas-deflecting walls, such as an expansion turbine at a compressor, to prevent erosion damage to such devices. Additionally, if the entraining gas is ultimately to be discharged to the atmosphere, the removal of particulate matter is also important from an environmental conservation standpoint.

Both of these considerations are present, for example, in the treatment of gases derived from the regeneration of cracking catalyst employed in a fluid catalytic cracking unit used in petroleum refining. The regeneration gas from such units generally contain entrained catalyst particles of the order of 1 to 75 microns in size which must be substantially removed from the gas before it can be passed to power recovery turbines or other means of recovering the latent energy contained therein. In addition, it is desirable to remove the catalyst particles from the regenerating gas to conserve catalyst and also to reduce particulate emissions to the atmosphere which has come under increasingly strict legislative regulation.

A number of systems and devices have been developed to effect separation of entrained solid particles from solid particle-bearing gases. Commonly employed in such systems are tubular centrifugal separators, also called cyclone separators, which are relatively simple devices comprising two concentric tubes, the inner tube serving as a gas outlet and vortex finder, while the outer tube serves as a swirl chamber in which the solid particles are centrifugally held against the wall and away from the vortex. Tangential velocity is imparted to the solid particles-bearing gas by means of swirl vanes located between the vortex finder and the swirl chamber, or by a tangential inlet. The separated particles are discharged from an opening in the bottom of the swirl chamber which usually has a conical shape, although swirl chambers having flat-bottom slotted tubes have also been disclosed, for example, in U.S. Patent Specification No. 3,066,854.

Cyclone separators of the type described above generally function effectively as long as the inlet and outlet gas flows are balanced. Unfortunately, however, systems in which such separators are employed are subject to periodic upsets or flow maldistributions, during which time larger than normal volumes of solids may enter the separators or erratic gas flows may be experienced. Under conditions of upset, most conventional separators do not perform satisfactorily because of inadequate solids discharge rates which cause accumulations of solid particles in the bottom of the tubes. These particles are eventually swept up and re-entrained in the gas leaving the vortex finder resulting in downstream erosion damage and excessive particulate emissions.

In systems employing multiple cyclone separators connected to a common gas source and a common particles collection chamber, reductions in separation efficiency are often experienced from non-external sources, i.e., through flow maldistributions within the separating apparatus per se. For example, when a number of such separators are connected in parallel, plugging of the tangential inlet or one or more slots of the swirl vane in one of the separators will cause a decrease in flow in that separator, with a corresponding increase in flow in the remaining separators. This results in "blowback" from the other separators into the partially blocked separator which is detrimental to separator performance causing

carry-over of particles. Flow maldistribution can also result from other conditions in the separation apparatus, for example, partial or total blockage of the vortex finder, excess clearance about the swirl vanes, and dents or other irregularities in the tubes, all of which also will adversely affect separation efficiency. In view of this it is apparent that the development of an apparatus for the separation of solid particles from solid particles-bearing gases which has a very high tolerance to upsets and internally caused flow maldistributions would be highly beneficial. The present invention provides such an apparatus, which is not only unexpectedly insensitive to flow maldistributions, but provides a number of additional advantages as well as hereinafter discussed.

According to the present invention an apparatus for separating finely-divided solid particles from an entraining gas, comprises means for supplying solid particles-bearing gas to a plurality of tubular cyclone separators arranged to operate in parallel and to discharge separated particles into a common collection chamber the cross-sectional area of which, at the discharge level of said separators, is greater than the combined cross-sectional areas of the discharge ports of said separators, the disposition of said separators being such that when said apparatus is in its operating position each of said separators is substantially upright, each of said separators comprising an open-ended tubular vortex finder lying partly within an open-ended swirl tube of substantially uniform diameter, which swirl tube is co-axial with said vortex finder and has, at its end remote from said vortex finder, a particle discharge port of substantially the same diameter as the swirl tube, and swirl vanes for introducing solid particles-bearing gas into the swirl tube with tangential velocity, said swirl vanes having a discharge angle of 30° or less (measured in the manner as hereinafter described).

Also, according to the present invention a method of separating finely-divided solid particles from an entraining gas comprises supplying solid particles-bearing gas to a plurality of substantially upright tubular cyclone separators, each of said separators providing a tubular swirl zone of substantially uniform diameter into which the gas is introduced with tangential velocity by means of swirl vanes having a discharge angle of 30° or less (measured in the manner as hereinafter described), withdrawing substantially particles-free gas upwardly from the vortex of the resulting swirling flow within each swirl zone, and withdrawing solid particles from the bottom of each swirl zone without flow restriction into a common collection zone of substantially greater cross-sectional area at the discharge level of said separators than the combined cross-sectional areas of the plurality of swirl zones at the bottom thereof.

Advantageously, the solid particles-bearing gas supplied to said plurality of cyclone separators is obtained by dividing a common input stream of such gas into an equal plurality of separate gas streams, and the gas withdrawn upwardly from each swirl zone is combined to form a substantially particles-free off gas.

The apparatus in accordance with the invention has been found to have an appreciably greater tolerance to upsets and flow maldistributions than systems employing separators having conical or slotted bottoms. The improved performance of the present apparatus during periods of external upset is understandable since the separators have no bottom on which the larger than normal volume of particles can accumulate; therefore, there can be no pile-up of particles and consequently less chance of particle re-entrainment. The reason for the improved efficiency during periods of internally caused maldistributed flows is more obscure, however, since it would be expected that swirl tubes with large unrestricted openings would be more susceptible to having solid particles swept up from the collection chamber into vortex finder by the backflow of gas, than swirl tubes having restricted openings. It is thought that outstanding performance of the present apparatus is due to the formation of a swirling, expanding circular gas barrier below each swirl chamber which prevents particles in the collection chamber from being swept into the vortex finder in the event of blowback. Such a gas barrier is not formed with conventional tubular cyclone separators, or is formed only to a substantially lesser extent, since the gas in the swirl tube of such separators loses its helical momentum upon passing through the restricted opening in the bottom of the swirl tube.

In addition to maintaining high separation efficiency under conditions of upset or maldistributed flow, the use of a plurality of cyclone separators with substantially unrestricted bottoms and having swirl vanes as defined has been found to increase the efficiency of separation during normal operation. This arises from the provision of swirl vanes set at the defined critical discharge angles as hereinafter discussed. The invention also offers advantages in respect of reduced erosion damage.

Ratios of the diameter of the vortex finder to the diameter of the swirl tube and other dimensions of tubular cyclones, in general, are well known in the art and need not be described in detail herein. The length of the bottomless swirl tube employed in the present apparatus is not critical, except that the swirl tube length should be less than the length at which substantial reversal of the gas flow would occur within the tube.

The present apparatus is especially suitable for separating catalyst particles entrained in regenerating gas obtained from a fluid catalytic cracking unit. An important feature of the present invention is the use of swirl vanes having a relatively small discharge angle, i.e., 30 degrees or less, measured from the lower surface of the vane to the horizontal as shown in Figure 3 of the accompanying drawings.

The use of swirl vanes having relatively small discharge angles increases tangential inlet velocity and correspondingly, the separation efficiency. However, the extent to which the angle of the vanes can be reduced in conventional separators is limited by the increased pressure loss and erosion damage to the separator walls which occurs as the vane discharge angle is reduced. It has been found, however, that such pressure loss and erosion are to a large extent nullified when bottomless swirl tubes are employed, thus permitting the use of smaller vane angles than in separators with restricted bottoms. This is highly advantageous in that it has been found that very fine solid particles, i.e., those having cut point diameters of 2.5 microns and lower, can be separated with bottomless separators having vane angles of 30 degrees or less. In contrast, the minimum cut point diameter particle which can be separated by most conventional separators in service is about 3 to 4 microns. The cut point diameter is defined as the smallest diameter particle which is separated at 50% separation efficiency. The separation of such extremely fine particles is, of course, highly advantageous for purposes of air pollution control as previously discussed.

The invention will be further described with reference to the accompanying drawings, in which:

Figure 1 is an elevation view, partly in section, of a separating apparatus embodying the invention and containing four tubular cyclone separators operating in parallel,

Figure 2 is an enlarged elevation, partly in section, of a cyclone separator suitable for use in the apparatus of Figure 1,

Figure 3 is a cross section of a swirl vane illustrating how the swirl vane angle is measured, and

Figure 4 is a graph showing the relationship between the percentage blowback and the gross efficiency of a conical bottom and a bottomless cyclone separator.

Referring to Figures 1, 2 and 3, gas containing entrained solid particles enters the separating apparatus through line 1 into distributing chamber 2 defined by vessel wall 3 and partition walls 4 and 5, whereby the gas is distributed to one of four tubular cyclone separators. While four cyclone separators are employed in the embodiment shown, it is understood that a lesser or greater number of such separators can be used. In the embodiment shown, the individual cyclone separators are equipped with swirl vanes 6 through which the gas passes and enters swirl tube 7 at a high tangential velocity. In the swirl tube the solid particles are centrifugally separated and are discharged through lower particle discharge port 9, which has a diameter substantially the same as that of the swirl tube, into a common collection chamber, defined by hopper 10 which has a cross-sectional area at the discharge level of said separators which is greater than the combined cross-sectional areas of the swirl chambers. The clean gas flows through vortex finder 8 into plenum chamber 11 and is discharged through duct 12, whereafter it may be passed to a power recovery turbine or other fluid dynamic device, or to the atmosphere.

In the embodiment shown in Figure 2 the tangential velocity is imparted to the solids-bearing gas by means of swirl vanes 6.

In Figure 3 it is shown how the swirl vane angle (in this case of the embodiments of Figures 1 and 2 it is 30°) is measured with respect to the horizontal.

It will be understood that the present separating apparatus may be used alone or in conjunction with other separating devices. For example, in fluid catalytic cracking units, three or more separation stages are often employed, each being adapted to remove increasingly smaller sized catalyst particles. The present separation apparatus may be employed in any of these separation stages, but, preferably, it is employed in at least one of the final stages because of the excellent separation efficiencies obtainable with small diameter particles as previously discussed.

The following examples are now presented to further demonstrate the invention and the advantages thereof.

EXAMPLE I.

To demonstrate the ability of the present apparatus to maintain separation efficiency in spite of maldistributed flows, a series of experiments was conducted in which an apparatus in accordance with the invention was subjected to several types of flow maldistribution, simulating conditions encountered in commercial operations. The apparatus in accordance with the invention which was employed in these experiments comprised four tubular cyclone separators equipped with swirl vanes and having bottomless swirl tubes through which separated catalyst was discharged into a common hopper. The solid particles-bearing gas employed in these experiments was air containing the designated amount of catalytic cracking catalyst, 96% of which had a particle size between 0.6 and 25 microns.

In one set of experiments, a number of vanes in one of the tubular cyclone separators was blocked causing excessive blowback

in that separator due to excessive blow-down in the remaining separators caused by handling the additional load of the blocked separator. This type of flow maldistribution is hereinafter referred to as Type 1 flow maldistribution. In another experiment, the vortex finder of one of the separators was plugged causing excess blow-down in the altered separator, with excessive blow-back in the remaining separators. This type of flow maldistribution is hereinafter referred to as Type 2 flow maldistribution. In a further experiment, Type 2 flow maldistribution was created by operating one of the separators with excessive clearance between the vanes and the wall of the swirl chamber which permitted larger than normal volumes of gas to enter the swirl tube of the altered separator.

The flow patterns in each of the experiments were established by helium tracer tests in which helium was injected into the vane slot of one swirl vane and helium concentrations measured in the air discharged from each of the gas outlets. With flow maldistribution, two separate sets of concentrations were measured—one with helium injected into the swirl vane slot of an unaltered tube and a second with helium injected into the swirl vane slot of the altered tube. The results of these experiments are shown in the following tabulation. The percent blowback for Type 1 flow maldistribution refers to blowback in the altered separator, while percent blowback with Type 2 flow maldistribution refers to blowback in the unaltered tubes. Gross efficiency (η) is calculated according to the equation $\eta = \frac{U}{F}$, where U is the total weight of the catalyst collected in the underflow from the separator, and F is the weight of the catalyst charge to the separator.

TABLE I

Exp. No.	Malfunction	Type maldistributed flow	Main flow rate, $Nm^3/sec.$	Catalyst charge, grams	Blowback, %	Gross efficiency, %
1	None (base case)	—	1.13	2028.5	- 1	61.6[1]
2	One vane slot plugged	1	1.13	1875.6	5.2	58.8
3	Two vane slots plugged	1	1.09	1946.6	25.8	51.1
4	Blocked vortex	2	1.16	2222.2	33.3	34.0
5	Excessive clearance, 3/16"	2	1.23	2211.3	3.8	57.3

1. Average of 3 runs

The foregoing data demonstrate that multiple-bottomless separators operating in parallel retain their separation efficiency to a substantial degree in spite of high blowback flows.

EXAMPLE II.

In this example a series of experiments was conducted comparing the ability of the bottomless tubular cyclone separators employed in the apparatus of the invention to withstand maldistributed flows as compared to a conical bottom separator, under varying conditions of blowback. One set of experiments was carried out with a bottomless tubular cyclone separator according to the invention having a 254 mm diameter swirl tube and swirl vanes set at 20° vane angle. In these experiments flow rates of from 0.49 to 0.51 $Nm^3/sec.$ were used. In another set of experiments tubular cyclone separators were used having a swirl tube with a conical bottom with a 38 mm opening and swirl vanes set at 30° vane angle. In these experiments a flow rate of 0.69 $Nm^3/sec.$ was used. The results of these experiments are graphically presented in Figure 4. The upper curve represents the experiments with the cyclone according to the invention. The solid particles-bearing gas employed in this comparison was the same as employed in Example I.

From the results shown in the graph it is

evident that while the gross separation efficiency of the conical bottom separator decreases sharply as the amount of blowback increases, the separation efficiency of the bottomless separator in accordance with the invention, although having a much larger opening than the conical bottom separator, decreases only gradually as blowback increases, and still retains a relatively high degree of separation efficiency at 15% blowback. In a further experiment, a bottomless tubular cyclone separator in accordance with the invention and having a 10° swirl vane angle was found to have a gross separation efficiency of approximately 54% at a blowback of 19%.

EXAMPLE III.

The advantages of the present invention were further demonstrated in a series of experiments wherein the separation efficiencies of the bottomless cyclone separators were compared to those of conventional separators at various vane angles. The conditions under which these experiments were run, and the results thereof, are shown in Table II. The size of the slots of the flat bottom separators was approximately 19.05 × 9.525 × 50.8 mm while the opening of the conical bottom was 25.4—12.7 mm. The bottomless separator had a 254 mm diameter unrestricted opening.

TABLE II

Exp. No.	Separator type	Vane angle, degrees	Main flow rate, Nm^3/sec.	Catalyst charge, g	Gross efficiency, %
6	Flat bottom- two slots	30	0.65	1506	60.0
7	Conical bottom	30	0.65	1492.0	66.4
8	Bottomless	30	0.71	1482.3	70.7
9	Flat bottom- two slots	20	0.46	1475.5	64.6
10	Conical	20	0.50	1333.0	73.0
11	Bottomless	20	0.52	1439.3	75.7
12	Flat bottom- two slots	10	0.33	1517.0	68.6
13	Bottomless	10	0.37	1425.6	74.8

In addition to determining the gross separation efficiencies in the above-mentioned experiments, the separation cut point was also determined in several of the runs. The results of these determinations are as follows:

TABLE III

Exp. No.	Separator type	Vane angle, degrees	Cut point diameter, μ
6	Flat bottom-two slots	30	3.3
8	Bottomless	30	2.5
11	Bottomless	20	1.86
13	Bottomless	10	1.65

The above data indicate that a reduction in cut point to below 2.5μ can be achieved by the use of bottomless separators having swirl vanes with a discharge angle of 30 degrees or less.

WHAT WE CLAIM IS:—

1. An apparatus for separating finely-divided solid particles from an entraining gas, comprising means for supplying solid particles-bearing gas to a plurality of tubular cyclone separators arranged to operate in parallel and to discharge separated particles into a common collection chamber the cross-sectional area of which, at the discharge level of said separators, is greater than the combined cross-sectional areas of the discharge ports of said separators, the disposition of said separators being such that when said apparatus is in its operating position each of said separators is substantially upright, each of said separators comprising an open-ended tubular vortex finder lying partly within an open-ended swirl tube of substantially uniform diameter, which swirl tube is co-axial with said vortex finder and has, at its end remote from said vortex finder, a particle discharge port of substantially the same diameter as the swirl tube, and swirl vanes for introducing solid particles-bearing gas into the swirl tube with tangential velocity, said swirl vanes having a discharge angle of 30° or less (measured in the manner as hereinbefore described).

2. A method of separating finely-divided solid particles from an entraining gas, which comprises supplying solid particles-bearing gas to a plurality of substantially upright tubular cyclone separators operating in parallel, each of said separators providing a tubular swirl zone of substantially uniform diameter into which the gas is introduced with tangential velocity by means of swirl vanes having a discharge angle of 30° or less measured in the manner as hereinbefore described, withdrawing substantially particles-free gas upwardly from the vortex of the resulting swirling flow within each swirl zone, and withdrawing solid particles from the bottom of each swirl zone without flow restriction into a common collection zone of substantially greater cross-sectional area at the discharge level of said separators than the combined cross-sectional areas of the plurality of swirl zones at the bottom thereof.

3. A method as claimed in claim 2, wherein the solid particles-bearing gas supplied to said plurality of cyclone separators is obtained by dividing a common input stream of such gas into an equal plurality of separate gas streams, and the gas withdrawn upwardly from each swirl zone is combined to form a substantially particles-free off-gas.

4. An apparatus as claimed in claim 1 and substantially as hereinbefore described with reference to Figures 1 to 3 of the accompanying drawings and/or to the Examples.

5. A method as claimed in claim 2 and substantially as hereinbefore described with reference to the accompanying drawings and/or to the Examples.

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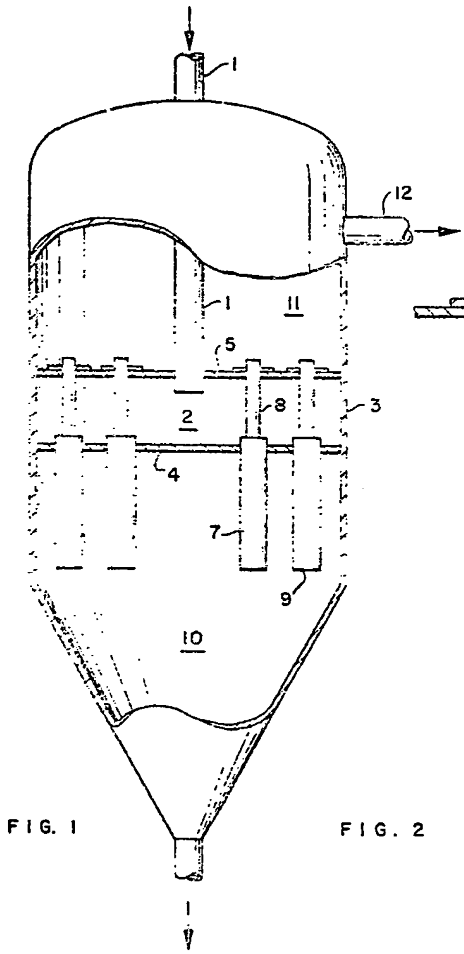

FIG. 1

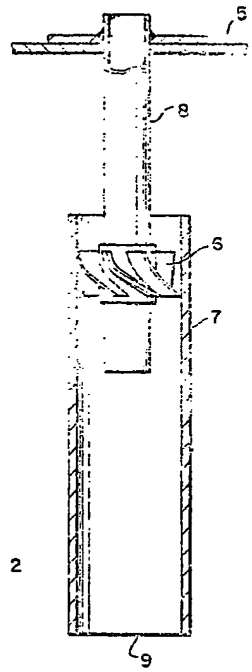

FIG. 2

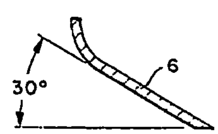

FIG. 3

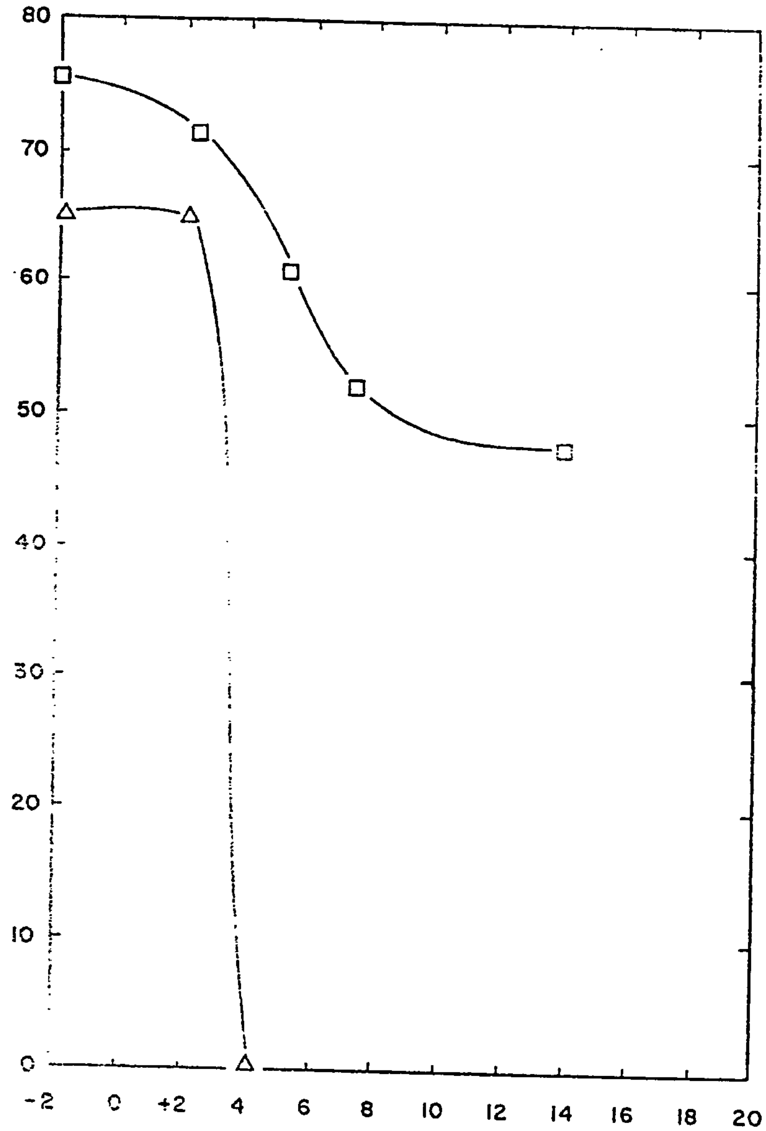

FIG. 4

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